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16. ABSTRACT

Remote sensing methods offer various advantages over contact measurement methods both for characterizing the gaseous and particulate air pollutants emitted by different types of sources and for verifying that established emission standards are being met by regulated industries. Two such instrumentation systems are in routine use for characterization studies: a mobile pulsed ruby lidar system measures stack plume opacity with an accuracy comparable to an in-stack transmissometer; and a mobile high resolution (0.1 cm^{-1}) infrared spectrometer system measures multiple gaseous species concentrations in a longpath absorption mode or in a single-ended emission mode with near-laboratory accuracy. A laser-Doppler velocimeter system for measuring the velocity of stack plumes and winds aloft has recently been obtained. Several systems particularly aimed at meeting the measurement needs of enforcement personnel are under evaluation. Tuneable laser systems for use in the longpath absorption mode and in the differential absorption lidar mode are in various stages of development. Research programs are underway to determine the feasibility of remotely measuring particulate size distributions and pollutant (gases and particles) mass emission rates. This paper presents results obtained with the instruments currently in use and summarizes the current state of development of the various other systems.

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Overview of the Environmental Protection Agency (EPA) programs for ground-based remote sensing of air pollution

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Abstract

Remote sensing methods offer various advantages over contact measurement methods both for characterizing the gaseous and particulate air pollutants emitted by different types of sources and for verifying that established emission standards are being met by regulated industries. Two such instrumentation systems are in routine use for characterization studies: a mobile pulsed ruby lidar system measures stack plume opacity with an accuracy comperable to an in-stack transmissometer; and a mobile high resolution (0.1 cm^{-1}) infrared spectrometer system measures multiple gaseous species concentrations in a longpath absorption mode or in a single-ended emission mode with near-laboratory accuracy. A laser-Doppler velocimeter system for measuring the velocity of stack plumes and winds aloft has recently been obtained. Several systems particularly aimed at meeting the measurement needs of enforcement personnel are under evaluation. Tuneable laser systems for use in the longpath absorption mode and in the differential absorption lidar mode are in various stages of development. Research programs are underway to determine the feasibility of remotely measuring particulate size distributions and pollutant (gases and particles) mass emission rates. This paper presents results obtained with the instruments currently in use and summarizes the current state of development of the various other systems.

Introduction

Remote sensing of air pollution actually began in the early 1900's with the use of "trained observers," who visually compared black stack plumes to a series of charts of graduated blackness (Ringelmann method). This concept was extended in the 1940's to plumes of different shades of greyness by training observers to determine the degree to which a plume obscured background light (opacity method). Although potentially subject to considerable error (on the low side) due to sky color and lighting conditions, the observer-opacity method has been used to establish opacity standards for particulate emissions. However, steps have recently been initiated to officially establish the lidar concept as an alternate method for determining plume opacity for both enforcement and standard-setting needs. Although not available as an off-the-shelf item, lidar systems for opacity measurements now consist of standard components and should be considered as a well-establish remote measurement method.

The first commercially available remote sensor for gaseous pollutants was developed by Barringer Research of Canada over ten years ago. This instrument uses the matched-filter correlation concept and measures SO_2/NO_2 optical depth in absorption with scattered ultraviolet/visible sunlight serving as a light source. Infrared techniques have been used on a research basis to measure atmospheric pollution for over twenty years.[1] There are no standard commercially available infrared remote sensors for air pollution measurements although the EPA is using routinely an especially equipped standard Fourier transform interferometer system (FTIS) for a variety of gaseous air pollutant measurements. Also, the gas-filter correlation (GFC) concept is well-established as an accurate method for measuring specific gas concentrations in the absorption mode and offers considerable promise for use in the single-ended mode (sensors utilizing this principal for in-situ measurement of auto exhaust and stack gas concentrations are commercially available).

In addition to measuring pollutant concentrations, it is also necessary to measure pollutant flow rates, since many of the EPA emission standards are based on a mass emission rate. The CO_2 laser-Doppler velocimeter (LDV) provides the necessary remote velocity measurement, although infrared and ultraviolet television (IRTV and UVTV) systems can provide similar data at the stack exit in certain cases. The IRTV can provide velocity data day or night but probably cannot provide concentration data. The UVTV system is limited to daytime use but can provide SO_2 concentration and opacity data, in addition to velocity. The LDV systems can provide wind or stack exit velocity measurements. The wind measurement is particularly applicable in measuring emission rates from extended area sources. This is of considerable importance, since the EPA has established the "bubble concept" whereby a industry such as an oil refinery would have to meet a total emission standard (e.g., for hydrocarbons) rather than a standard for individual sources within the refinery. Only remote sensing techniques can adequately determine the emissions from such extended area sources. (By measuring the pollutant optical depth in a vertical column surrounding a source and the wind velocity, the pollutant mass emission rate can be determined.)

Laser systems offer considerable promise in the area of remote sensing of gases in that they can provide range-resolved and three dimensional concentration data. Two-ended systems utilizing CO_2 and diode lasers have been developed for EPA, and low level funding of research on the differential absorption lidar concept has occurred over the past ten years or so. Principal difficulties of the laser systems, as compared with conventional spectroscopic systems, are lack of frequency and intensity stability and lack of ability to reach all desired wavelengths. The development of these systems and the solving of such problems has proven time consuming and relatively expensive. Fortunately other government agencies have interest in the development

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of laser systems for remote measurement of gas concentrations, and much of the work in this area has been supported by Air Force, NSF, NOAA, and NASA funds (and recently, funds from the DOE and the EPRI). The various laser systems being developed under the NASA Environmental Quality programs have been discussed in the previous paper, along with some of airborne remote sensing work that is being conducted at the EPA Las Vegas laboratory.[2]

The remainder of this paper will disucss recent results and current activities within the EPA intramural and extramural ground-based remote sensing programs. For a complete discussion of essentially all remote sensing techniques applicable to measurement of source emissions the reader is referred to the work of Ludwig and Griggs.[3]

Instrumentation

Lidar for opacity measurements. The lidar technique for remote measurement of plume opacity was first demonstrated by Evans,[4] who used lidar equipment designed for atmospheric studies. He showed that the opacity and transmittance of a plume could be determined by aiming the laser beam through the plume and comparing the relative backscatter intensity of the beam by the atmosphere in front of and behind the plume. In 1972, a van-mounted lidar designed for plume opacity measurements was developed for EPA by General Electric Company. The operating characteristics of the system are given in Table 1.

Table 1. Mobile Lidar System Characteristics

Component	Characteristic	Component	Characteristic
Transmitter		Receiver	
Laser	Rotating prism, Q-switched ruby	Objective lens	15.25 cm, f/5
		Field-of-view	4 miliradian full angle
Wavelength	694.3 nm	Bandpass (FWHH)	1.2 nm
Pulse width (FWHH)	<30 nanoseconds	Photomultiplier	IT&T F4084 (modified S-20)
Maximum output	1.0 joule	Off-gating	±60 dB
Repetition rate	3 pulses per minute	Response	∿100 nanoseconds
Cooling	Deionized water		
Objective lens	12.7 cm, f/5		
Beam divergence	∿0.5 miliradian full angle		

The accuracy of the lidar system was determined by using neutral density screen targets of known opacity. The opacity of 1-m diameter screens was determined by laboratory transmissometers, which were in turn calibrated by using Kodak Wratten neutral density filters. The lidar opacity measurements of the calibrated targets were made at a distance of 200 m. The results indicated that the lidar is accurate to within 3% opacity for opacities less than 50%. At higher opacities the results showed maximum error of about -15% opacity for a targeted opacity of 100%. This decline in accuracy for high opacities is of little concern since no opacity standards for emission sources are above 50% opacity. Agreement between lidar and in-stack transmissometer measurements of opacity are excellent; correlation coefficients of 0.996 are typical.

The EPA lidar system and associated measurements are described in detail in the literature.[5,6,7] Specific ongoing work in this area includes development of a low-cost lidar system, determining relationships between opacity and mass density, and development of a system for remote determination of particulate size distributions. (The lidar work at EPA/RTP is directed by William D. Conner.) Recently, the EPA National Enforcement Investigation Center in Denver has obtained a similar lidar system. The data obtained with these two systems is being used to establish the lidar method as an alternate Reference Method for opacity measurements.

Fourier transform interferometer system. About three years ago a Nicolet Model 7199 was configured to fit into an existing van. The FTIS replaced a grating monochromator system and is matched to a Dall-Kirkham telescope (30 cm diameter primary mirror) to collect infrared energy either from a remotely located light source (with identical telescope) or from warm gases exiting industrial stacks. A flat tracking mirror is used to assist in sighting on stack exits (or to obtain solar spectra). Measurements of gas pollutant concentrations have been made at a variety of pollutant sources, e.g., water treatment ponds at phosphate fertilizer plants, jet engines, coal-burning power plants, and waste gas flares.[8,9] On a recent measurements program the system line of sight was across the top of a brick kiln (30 x 17 x 7 meters, 1.2 million bricks). The bricks are gas-fired over a period of three days until the entire kiln reaches a temperature of approximately 1500°K. Typical spectra obtained are shown in Figure 1. Spectra obtained at other sources are shown in Figure 2. The FTIS, which has the acronym ROSE (Remote Optical Sensing of Emissions) system, has proven a highly useful and versatile instrument for characterizing source emissions.

Laser Doppler Velocimetry. Since emission standards for stationary sources are generally based on a mass-emission rate, it is necessary to measure effluent velocity as well as concentration by remote methods to take full advantage of remote-sensing techniques. The LDV technique has been in use for about 10 years to make non-contact velocity measurements in experiments concerning wind tunnels, clear-air turbulence, wake vortices and atmospheric winds. In this method a CO_2 laser beam is propagated through the atmosphere and brought to focus at the desired range. Aerosols in the atmosphere or in a plume scatter a fraction of the laser energy back toward a receiving telescope. Since the aerosol particles are in motion, backscattered energy will be shifted in frequency from the outgoing laser beam because of the Doppler effect. The shift in

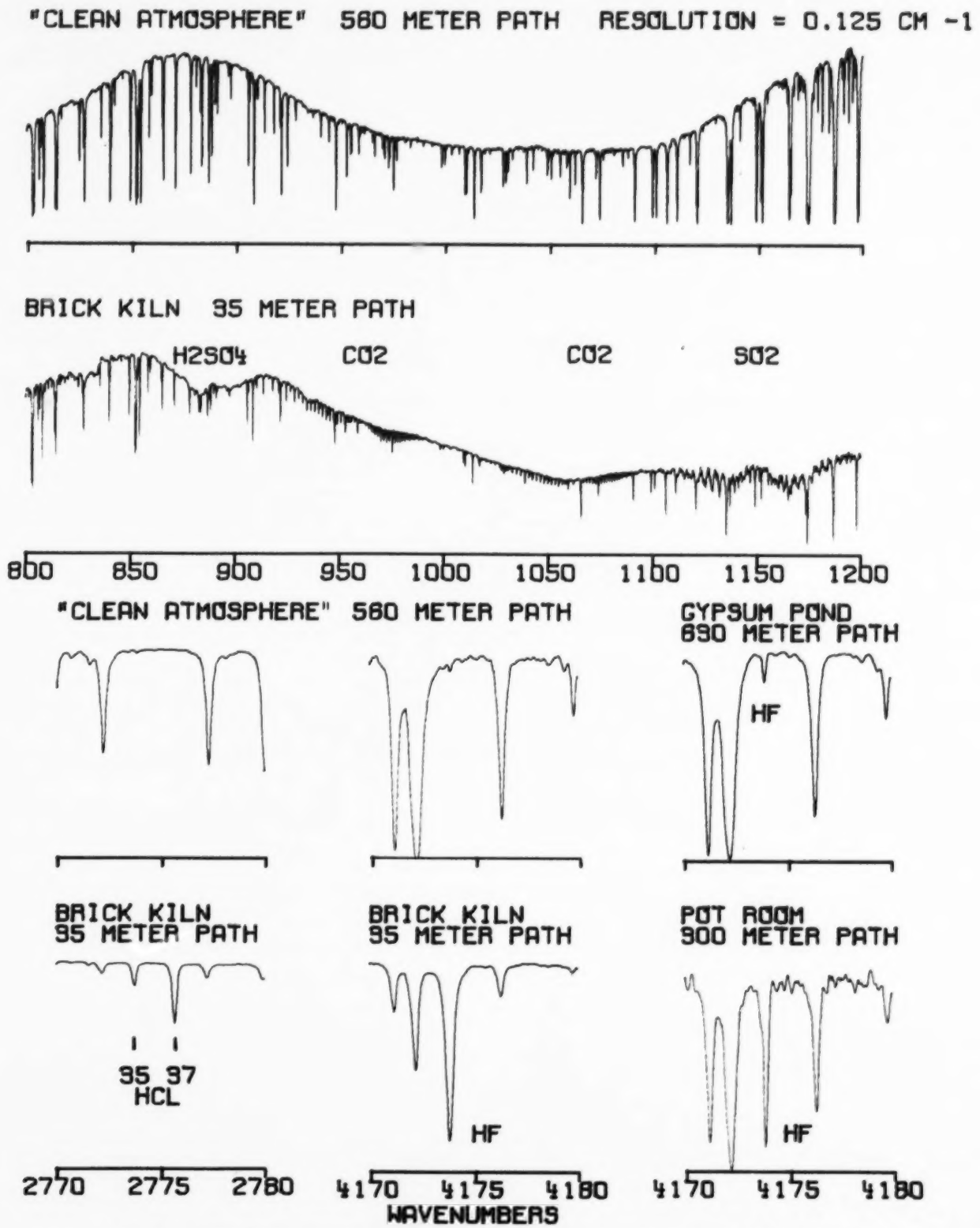

Figure 1. Absorption spectra of brick kiln emissions and of HF from several sources.

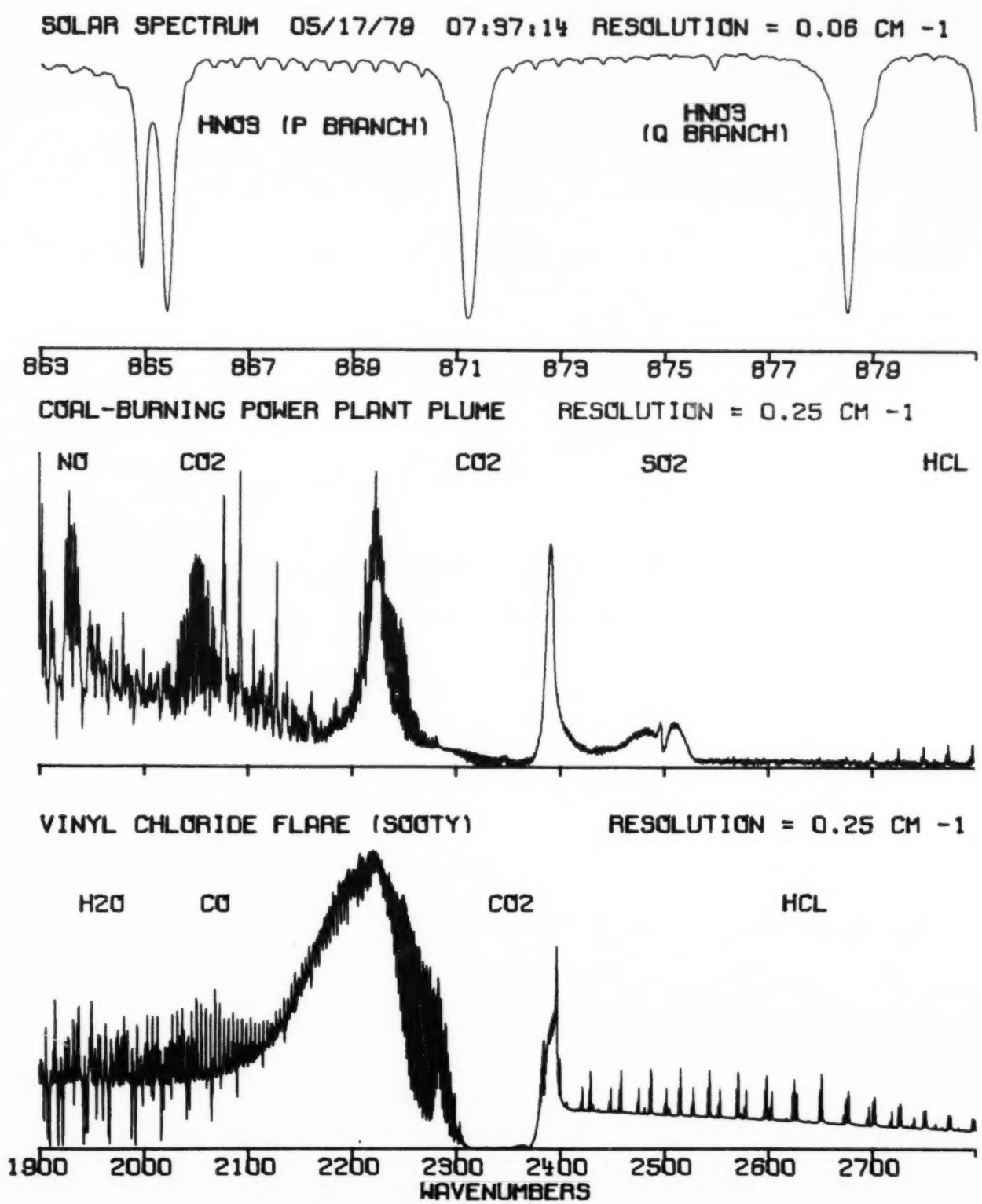
SOLAR SPECTRUM 05/17/78 07:37:14 RESOLUTION = 0.06 CM -1
HNO3 (P BRANCH)
HNO3
(Q BRANCH)
863 865 867 869 871 873 875 877 879
COAL-BURNING POWER PLANT PLUME RESOLUTION = 0.25 CM -1
NO CO2 CO2 SO2 HCL
VINYL CHLORIDE FLARE (SOOTY) RESOLUTION = 0.25 CM -1
H2O CO CO2 HCL
1900 2000 2100 2200 2300 2400 2500 2600 2700
WAVENUMBERS

Figure 2a. Typical ROSE system spectra (solar absorption and hot gas emission).

frequency depends on the laser wavelength and the velocity component along the laser beam. The backscattered energy and a fraction of the outgoing laser beam fall on the same detector, and the difference in frequency is detected by conventional heterodyne techniques.

In order to determine the feasibility of remotely measuring stack effluent velocity by LDV, a program was undertaken using an existing LDV system at a coal-burning power plant. Measurements were conducted in August 1974 and January 1975, and the results have been described in detail by Miller and Sonnenschein.[10] Although the primary aim of the program was to demonstrate the feasibility of the remote velocity measurements, a secondary aim was to determine what, if any, relationship exists between the intensity of the backscattered signal and the attenuation coefficient of the plume (as determined from the opacity of the plume). It was shown that a reasonably linear relationship exists between plume attenuation coefficient and mass density for a given type of particulate source. Thus, the LDV measurement, utilizing a single instrument, has the potential to give a mass-emission rate for particulates.

Analysis of the velocity measurements found the LDV values within 14% of the in-stack values obtained by using EPA Reference Method 2. Since Reference Method 2 is considered accurate to ±20%, the agreement is about as good as might be expected. Although only two sets of data relating backscatter signal strength to plume attenuation coefficient were obtained, there is certainly good indication that a linear relationship exists. This relationship, if verified by additional measurements on a variety of sources, would allow a single LDV instrument to be used to measure a particle mass-emission rate when calibrated empirically for each type of source. Other measurements have shown that the use of an LDV system (as opposed to pilot balloons or other conventional wind measuring methods) can significantly enhance the accuracy of remote mass emission rate measurements for SO_2.[11] (In this "uplooking" perimeter mode the SO_2 optical depth is measured in a vertical column surrounding the source in question. By also measuring the local wind velocity, the SO_2 mass emission rate from the source may be calculated.) Raytheon Corporation has recently designed and fabricated a mobile LDV system for the EPA. After an intensive evaluation of the system by NOAA's Wave Propagation Laboratory, the system will be used for further studies on gaseous and particulate mass emission rate measurements.

Gas-Filter Correlation Instruments. The EPA has had a number of GFC instruments built under contract for measurement of auto exhaust emissions and for in-situ smoke stack measurements.[12] These instruments, along with a longpath version (for SO_2 and CO at pathlength up to a kilometer) have worked very well. The longpath instrument can be converted to a passive instrument for stack exit measurements. Another GFC instrument also operates in the passive mode but is used in an uplooking configuration to sense ambient temperature pollutants against the "cold" sky background. Preliminary measurements show that the two passive instruments, which have applications in the enforcement area, do work, but time has not allowed a thorough evaluation of these instruments. These evaluations should be completed by mid 1980. It is planned to sensitize the longpath model for HF and evaluate the instrument at an aluminum refinery for measurement of pot room HF emissions in early 1980.

UV and IR television. A UVTV system for monitoring SO_2 mass emission rates has been developed by Dr. Reggie Exton of NASA/Langley Research Center and is now commercially available. The SO_2 concentration data are obtained by filtering the TV camera first at 340 nm, where particulate opacity is measured, and then at 310 nm, where particulate opacity plus SO_2 opacity are measured. From these two measurements, the SO_2 attenuation can be determined and the concentrations calculated. Calibration is obtained by sighting the TV camera through cells that contain known amounts of SO_2. Effluent velocity is determined by tracking fluctuations in the SO_2 concentration as they move downstream. These fluctuations are actually large scale eddies which are produced at the stack lip as the flow mixes with the ambient air. The system electronics measures the average distance moved by the fluctuations in a given time interval. The resulting velocity is referred to as the eddy convection velocity. Measurements in the field on a variety of stacks have established a linear relationship between the eddy convection velocity and the mean velocity determined from in-stack measurements (EPA method 2). The system has the potential for measuring plume particulate opacity, but this has not yet been demonstrated.

The IRTV system, which is a dual channel commercial system covering the 3-5 and 8-14 micron regions is used for plume visualization at the present time. It is planned to couple the IRTV output to the UVTV system electronics for velocity measurement studies. (The IRTV has the advantage over the UVTV of night time operation.) It is not expected that the IRTV will be able to measure pollutant concentrations.

Summary

A mobile lidar system for plume opacity measurements and a mobile Fourier transform interferometer system for multiple gas concentration measurements are in routine use in the EPA remote sensing program. Laser-Doppler velocimetry, which is a well-proved concept, will soon join our fleet of mobile remote sensing systems and will be used in studies related to the remote determination of pollutant mass emission rates. The gas-filter correlation and television systems have excellent potential for routine surveillance or enforcement activities, but further evaluations are needed.

Acknowledgment

Some of the general concepts presented here were first described by Herget and Conner in "Instrumental Sensing of Stationary Source Emissions" Environmental Science & Technology, Vol. 11, 962-967 (1977).

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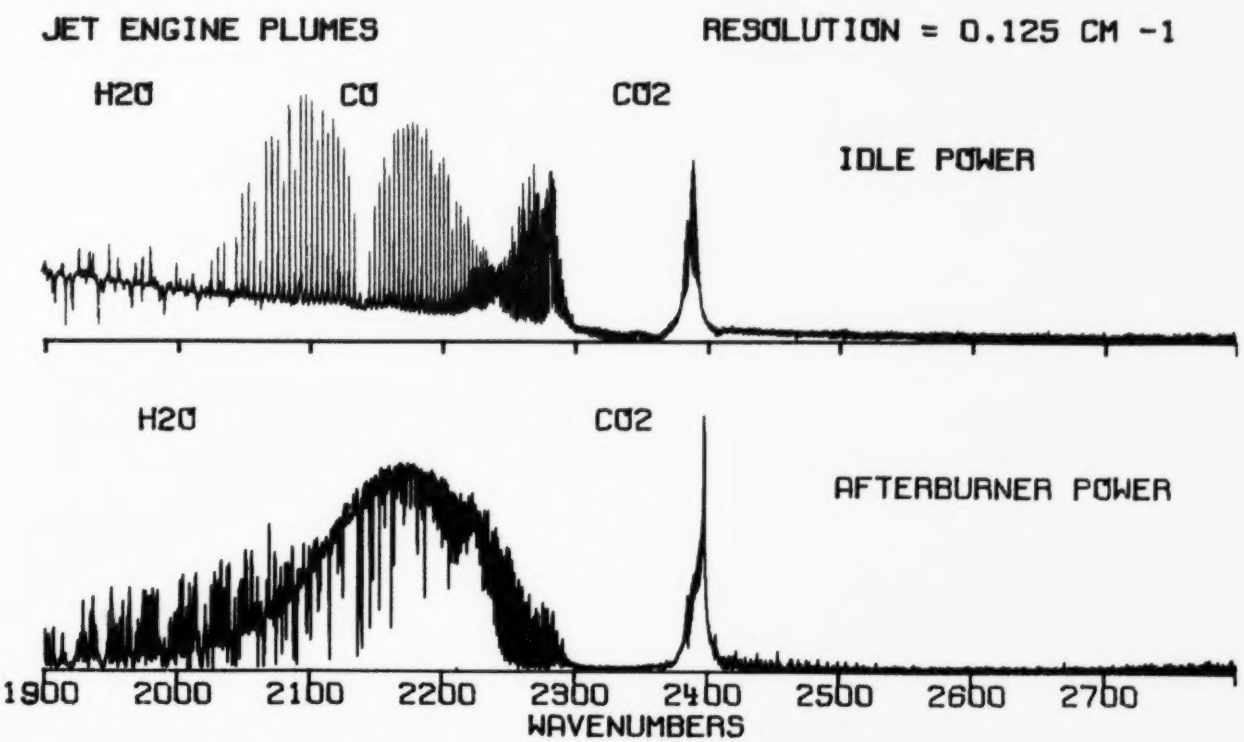

Figure 2b. Typical ROSE system spectra (emission from jet engine plumes).